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The Formation of Planetesimals: Building Bricks for Planetary Systems

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The asteroids[a] and Kuiper Belt objects[b] are left overs of building material for our earth and the other planets in our solar systems from 4.567 billion years ago. Those typically 100 km large objects are called planetesimals, built up from icy and dusty grains. In our current paradigm of planet formation it was turbulent flows and metastable flow patterns like zonal flows and vortices that concentrated mm to cm sized grains in sufficient numbers that a streaming instability and gravitational collapse of these particle clumps was triggered. The entire picture is known as gravoturbulent formation of planetesimals. What was missing until recently was a physically motivated prediction on the typical sizes at which planetesimals should form via this process. Our old simulations on JUGENE in Jülich had only shown a correlation between numerical resolution and planetesimal size and thus no answer was possible. But with the latest series of simulations on JUQUEEN[1] covering all the length scales down to the physical size of actual planetesimals we were able to obtain values for the turbulent particle diffusion as a function of the particle load in the gas. Thus we have all necessary data at hand to feed our back of the envelope calculation that predicts the size of planetesimals as result of a competition between gravitational concentration and turbulent diffusion. Using the diffusion values obtained in the numerical simulations on JUQUEEN predicts planetesimal sizes on the order of 100 km, which luckily coincides with the measured data from both asteroids[2] as well from Kuiper Belt objects[3].

1 Introduction

Planet formation is a beneficial side effect of star formation. It is the gas and dust around young stars that does not get accreted directly during the collapse of a cloud core due to angular momentum conservation that will form a planetary system. The goal of our current research activities is to better understand the properties and diversity of planets around distant stars as well as in our own solar system. Starting with numerical simulations of the star formation process we aim to understand the stages of disk formation and thus via a calibration on actual disk observations the initial mass and angular momentum distribution of disks as initial conditions for planet formation. In these disks we study all possible sources of turbulent disk evolution from self-gravity, via magnetic fields to classical hydrodynamical instabilities. Latest developments in the field include deriving various observables for different sources of turbulence, which in conjunction with simulations of planet disk interaction are used to interpret the wealth of observations coming online from interferometers working with many kilometre sized base-length in the submillimetre band (e.g. the Atacama Large Millimeter Array: ALMA[4]) to modern high resolution and high contrast cameras on the largest optical telescopes (e.g. SPHERE[5]). Lastly we follow all evolutionary steps of planets from small dust grains and snow flakes via planetesimals to

[a]More precisely: objects in the main asteroid belt.

[b]More precisely: objects in the cold classical Kuiper Belt.

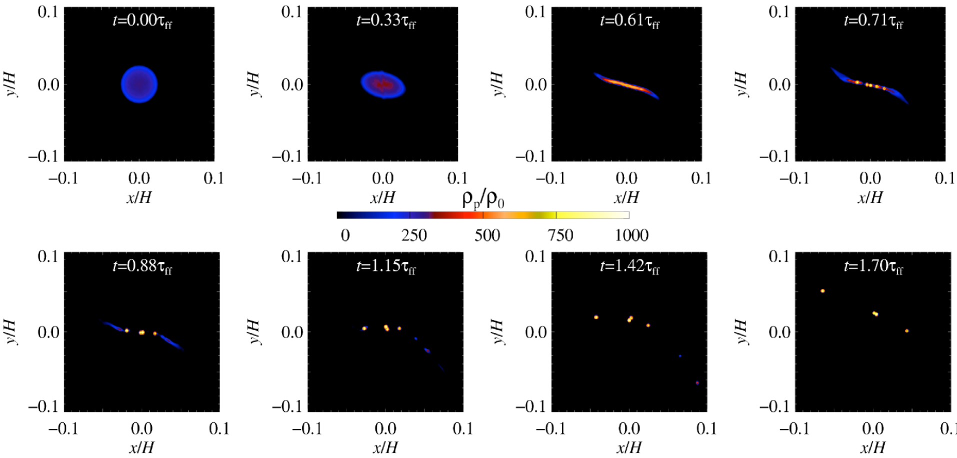

Figure 1. A series of snapshots following the collapse of a particle heap at 10 % of the local Roche density (see text) under its own gravity embedded in an accretion disk around a young star. Colours indicate the particle density. The initial spherical cloud gets sheared apart by Keplerian shear, or in other words by the tidal forces exerted from the star, because its internal density is lower than the local Roche density. Then its local subregions that exceed the Roche density, collapse into a group of many planetesimals around 100 km in size. This 3D Hydro Dynamical Simulation was performed with the Pencil Code on the JUQUEEN cluster (see PhD thesis by Karsten Dittrich[10]).

rocky and gaseous planets, partly in order to feed population synthesis with better data, partly to better interpret disk observations, and partly to study the chemical composition of planets - a question of special relevance to understand the formation of life on earth and elsewhere.

In a series of papers[6–8] we explained the formation of planetesimals via the process of gravoturbulence. Here it is magnetic fields that trigger the formation of zonal flows, which in turn concentrate particles up to dust to gas ratios of order unity. Then a second instability kicks in, based on the feedback of the dust onto the gas - the streaming instability. The action of this instability is twofold: A: it concentrates the dust even further up to values that locally exceed the Roche density[c] and B: destroying local particle concentration via turbulent diffusion on small scales. Exceeding the Roche density is the condition that self gravity is locally stronger than the tidal forces from the star, i.e. object or particle clumps of lower density than the Roche density will not collapse but get tidally sheared apart (see Fig. 1 from the PhD thesis of Karsten Dittrich[10]). Also comets are known to break apart once they pass the gravity field of a planet in a way that their internal density is lower than the local Roche density set by the planets mass and the distance from its centre (see the breakup of comet Shoemaker-Levy 9 (SL9)[9] and its following impact on Jupiter). In the case that gravity wins, e.g. that the local density exceeds the Roche density, a planetesimal can form. In Fig. 1 one finds that even the initial cloud is sheared apart, it forms fragments, which individually can exceed the Roche density and then form planetesimals. Unfortunately the regions that exceed the Roche density are at the resolution limit of our

[c]Roche density is the density that a gravity bound body needs to withstand the tidal forces of a second more massive body, for instance a close by planet or here: the sun.

numerical grid. Therefore we started looking for a physical criterion on the smallest possible fragments, that would withstand the tidal forces, while still resolving the turbulence of the gas.

A particle clump at Roche density without any internal pressure will collapse on the free fall time $t_{\mathrm{ff}} = 0.64\Omega^{-1}$ with Ω being the local Keplerian frequency around the central star. Yet as particles feel friction with the gas during their gravitational contraction, this time gets longer proportional to the friction time τ_{f}[d] defined via $\dot{v} = -\frac{\delta v}{\tau_{\mathrm{f}}}$. For typical particle sizes in protoplanetary disks the dimensionless friction time is given as the Stokes Number[e] $St = \tau_{\mathrm{f}}\Omega$ with values of about $St = 0.1$ Our numerical simulations[11] on particle growth and disk evolution have shown that larger Stokes numbers, i.e. larger particles will rarely by available, because they either rain out towards the sun, or destroy each other by collisional fragmentation.

In the case of Stokes numbers smaller than unity the particle clump contraction time (or sedimentation time for the case of self gravity) is on the order of $t_{\mathrm{s}} \approx \frac{t_{\mathrm{ff}}}{St}$[12]. Yet if the local dust concentration is diffused via the turbulent dust and gas motion with diffusivity D, a clump of size l gets diffused on the typical time scale of

$$t_{\mathrm{d}} = l^2/D. \tag{1}$$

If one compares now the time scale of diffusion versus sedimentation $t_{\mathrm{d}} = t_{\mathrm{s}}$ one can derive a size prediction of clumps to withstand internal diffusion at

$$l \approx \sqrt{\frac{D}{St\Omega}}. \tag{2}$$

In combination with the knowledge that the clump had already Roche density one can determine the mass of the resulting planetesimal as $m_P = \frac{4}{3}\pi l^3$. What remains to be determined is the diffusivity D for typical dust-to-gas-ratios and length-scales at which planetesimal formation is thought to occur.

2 High Resolution Studies of the Streaming Instability

Hydro- and magneto-hydro-dynamical instabilities lead to non-laminar flows within protoplanetary disks[13,14]. Many of those non-laminar features are known to produce dust overdensities via the local trapping of radially sedimenting particles (sedimentation towards the central star), such as zonal flows, and vortices, resulting in axisymmetric and non-axisymmetric structures[15]. Though they are short-lived in terms of viscous disk evolution, they are long-lived in terms of the disk dynamics. In particular, the concentration of dust as well as the collapse of a particle clump to a planetesimal is supposed to occur within a few local orbits. As shown in several papers in the last years particle overdensities are self amplifying over a certain threshold due to the streaming instability (SI)[16], which was numerical investigated at least for the largest possible scales ($\approx 0.1H$)[17].

[d] The friction time describes the friction between a particle of given mass and size with the surrounding gas. If particles are smaller than the mean free path of the gas, the drag formulae for the Epstein regime have to applied, otherwise the aerodynamic, i.e. Stokes drag is valid.

[e] In astrophysics the Stokes Number is defined on the global dynamical time scale of the system, i.e. the orbital frequency of the accretion disk, rather than via the unknown timescale relevant for the dissipation scale. Particles of $St = 1$ are then the fastest radially sedimenting objects in the radially pressure supported accretion disk.

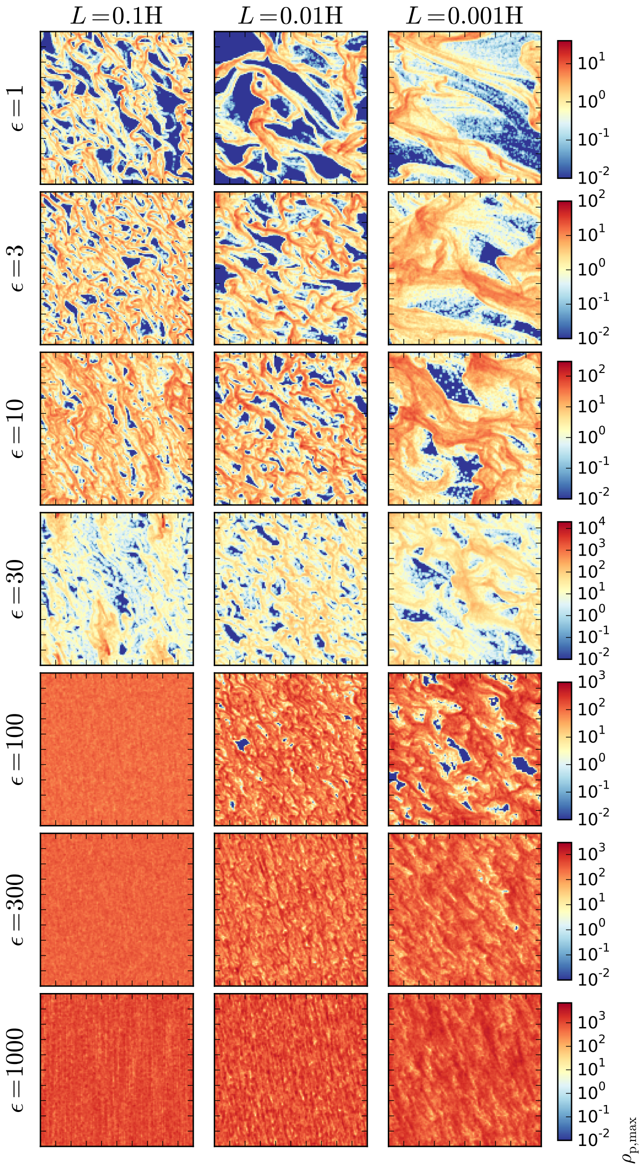

Figure 2. Overview of our parameter study to estimate diffusivities for the streaming instability on small physical length scales $L = 0.1\,H$ to $L = 0.001\,H$. We thereby investigate high dust to gas density ratios ϵ from 1 up to 1000, to mimic a wide range of phases within a collapsing particle clump. Colour represents the local dust to gas ratio with red high and blue low values.

Following this idea planetesimal collapse must happen in areas where SI is already active and will still be active during the collapsing phase. Here one can expect that for

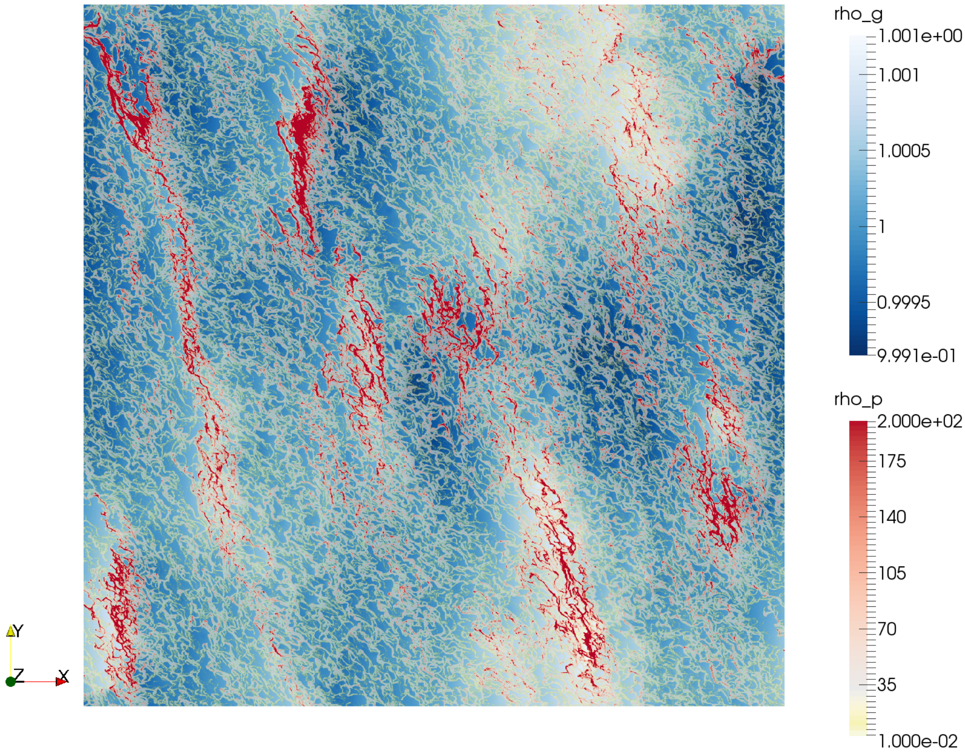

Figure 3. This snapshot shows the largest streaming instability investigation so far, with a resolution of 1250^2 and $1.6e7$ swarm particles. This snapshot shows in blue the underlying gas density field. On top of it in red to white is plotted the particle density. The particles show a typical streaming instability pattern over the whole domain (white) and additionally (red) particle dominated regions which are long lived and highly particle concentrated.

large dust-to-gas-ratios $\epsilon = \rho_{\rm p}/\rho_{\rm g}$ the SI should become weaker, because in the extreme case of having only dust, there are no more hydro-instabilities, and this is indeed what we see for numerical simulation at high ϵ-values.

Thus in a forthcoming paper we investigate if the SI can lead to diffusivities D or diffusion times expressed in local orbits that can delay or even prohibit the collapse to planetesimals via internal diffusion of the clump. Since the dust-to-gas-density-ratio ϵ will increase to very high numbers in the collapse phase, we will exceed ϵ-values previously investigated about several orders of magnitude see Fig. 2 for our scanned parameter space. Our boxes range from $L = 0.1H$ down to $L = 0.001H$ and the ϵ values increase from $\epsilon = 1$ to $\epsilon = 1000$. Depending on the local gas density, which is a function of time and space, the Roche density can be reached at values of $\epsilon = 10 - 1000$. Our 3D simulations use typically several Mio. CPU-hours per parameter set, which explains that scanning the necessary parameter space is a very expensive endeavour. We found that for increasing dust-to-gas-ratios the SI was getting indeed a little weaker, but nevertheless did not die out. At the same time the unstable wave-lengths were squeezed to smaller scales, e.g. the scales interesting for the final collapse - sedimentation phase of the planetesimal (see Fig. 4).

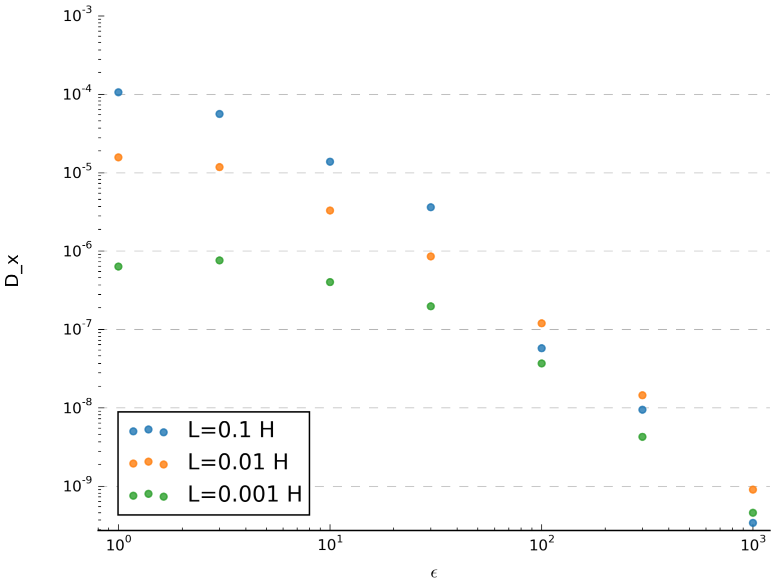

Figure 4. One of our results from our parameter study is a dust to gas ratio ϵ dependence of the diffusivity. This is the input for our planetesimal collapse scenario and will give us the ability to calculate planetesimal properties, such as size and rate.

3 Size Prediction for Planetesimals

The dust-to-gas-ratio that corresponds to the local Roche density depends on the distance from the star as well as on the actual gas content of the disk as a function of the evolution of the disk. As a typical value we choose $\epsilon = 10$ for distances of about 40 AU (= Astronomical Unit = distance Sun-Earth). The measured diffusivities at the medium scale $L = 0.01H$ in dimensionless units are $D = 2.7 \times 10^{-6}$. This value for D can be plugged into our prediction for planetesimal size a:

$$a \approx \frac{H/R}{0.03}\sqrt{\frac{D}{2.7\times10^{-6}}}\sqrt{\frac{0.1}{\mathrm{St}}}88\mathrm{km}. \tag{3}$$

This result is remarkably close to the measured sizes of the knee in the observed population of both asteroids and planetesimals and a nice support for our theory of planetesimal formation. An improved prediction of the actual gas content of the disk and the Stokes number of the available dust grains can still change the result, yet not by orders of magnitude.

4 Outlook

Of course, we have to refine our methods in several ways. For instance, we have to study the streaming instability for other particle sizes (e.g. St) as well as for entire particle size distributions. We also have to study the effect of particle-particle collisions in a better way, as they will eventually start to dominate, once we resolve the actual dimensions of the resulting planetesimal.

On the other hand we will surely test our back of the envelope estimate for the criterion of planetesimal formation via straight forward 3D numerical simulations of the streaming instability and gravitational collapse along the parameters as predicted from our non-self-gravitating runs. Then a high resolution case of fully developed SI as already obtained (see Fig. 3) will be the initial state, for which we "simply" have to switch on self-gravity and see A: whether the box size allows for collapse, e.g. the unstable wavelength as determined from diffusivity and self gravity fits into the simulation domain and B: whether the resulting planetesimals obey our size prediction, hopefully independent on further increasing the resolution, i.e. reaching convergence with resolution for our simulations. Then we will be able to say how the planetesimals in our solar system can have formed and explain the size of asteroids and Kuiper belt objects.

After that we can start investigating at what rate they were forming in the solar nebula. When did they form at what distance from the start? Where did their building material come from? What kind of planetesimals did form the earth and does it help us to understand the chemical composition of the earth? Finally this leads to the question of what were the chemical conditions on a young earth, which one day started to harbour life.

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